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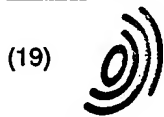
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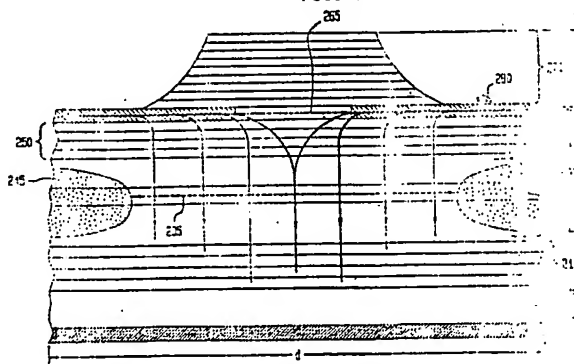
This application was filed on 12 - 08 - 1998 as a
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under INID code 11.

(54) Vertical-cavity surface-emitting lasers with intra-cavity structures

(57) Vertical-cavity surface-emitting lasers (VCSELs) are disclosed having various intra-cavity structures to achieve low series resistance, high power efficiency, and TEM₀₀ mode radiation. In one embodiment of the invention, a VCSEL comprises a laser cavity disposed between an upper and a lower mirror. The laser cavity comprises upper and lower spacer layers sandwiching an active region. A stratified electrode for conducting electrical current to the active region is disposed between the upper mirror and the upper spacer. The stratified electrode comprises a plurality of alternating high and low doped layers for achieving low series

resistance without increasing the optical absorption. The VCSEL further comprises a current aperture as a disk shaped region formed in the stratified electrode for suppressing higher mode radiation. The current aperture is formed by reducing or eliminating the conductivity of the annular surrounding regions. In another embodiment, a metal contact layer having an optical aperture is formed within the upper mirror of the VCSEL. The optical aperture blocks the optical field in such a manner that it eliminates higher transverse mode lasing.

FIG. 9



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Description

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application is related to our co-pending application serial No. 07/790,964, filed November 7, 1991, for "Visible Light Surface Emitting Semiconductor Laser," which is incorporated herein by reference.

FIELD OF THE INVENTION

[0002] This invention relates to semiconductor lasers and, more particularly, to vertical-cavity surface-emitting lasers that utilize intra-cavity structures to achieve low series resistance, high power efficiency, and single transverse mode operation.

BACKGROUND OF THE INVENTION

[0003] Vertical-cavity surface-emitting lasers (VCSELs) emit radiation in a direction perpendicular to the plane of the p-n junction or substrate rather than parallel to the plane of the p-n junction as in the case of conventional edge-emitting diode lasers. In contrast to the astigmatic beam quality of conventional edge emitting lasers, VCSELs advantageously emit a circularly symmetric Gaussian beam and thus do not require anamorphic correction. VCSELs, moreover, can readily be made into two-dimensional laser arrays as well as be fabricated in extremely small sizes. Accordingly, two-dimensional VCSEL arrays have various applications in the fields of optical interconnection, integrated optoelectronic circuits and optical computing.

[0004] To achieve a low threshold current, VCSELs typically utilize a thin active region on the order of $\lambda/4n$ thick or less, where λ is the wavelength of the emitted light and n is the index of refraction of the active region. With such a thin active region, however, VCSELs have a single pass optical gain of approximately 1% or less, thereby requiring the use of end mirrors having reflectivities greater than 99% to achieve lasing. Such a high reflectivity is normally achieved by employing epitaxially grown semiconductor distributed Bragg reflector (DBR) mirrors.

[0005] DBR mirrors comprise alternating high and low index of refraction semiconductor layers. For a reflectivity greater than 99%, between 20-34 pairs of such alternating semiconductor layers is typically needed, depending on the difference between the refractive indices of the layers. Doped with the appropriate dopants to have opposite conductivity types, the DBR mirrors form with the active region a p-i-n structure. Current injection is facilitated by making electrical contacts to each DBR mirror such that electrons and holes traverse through the mirrors to reach the active region, where they combine and generate radiation.

[0006] Unfortunately, the VCSEL's applicability is severely limited by its low optical power output. Particu-

larly, VCSELs have not been able to achieve comparable optical power output levels to those of edge-emitting lasers. The total power efficiency of VCSELs is presently limited to less than approximately 10%, whereas edge-emitting lasers routinely exhibit power efficiencies over 50%.

[0007] The VCSEL's low power efficiency results from two contributing factors: (1) low electrical conductivity, and (2) low optical quantum efficiency. The low-electrical conductivity is caused by the small cross-sectional area of the active region, i.e., the current conduction area, and the high resistance associated with electron and hole transport perpendicular to the plane of the multilayered DBR mirrors. The optical quantum efficiency of the VCSELs, however, is related to the optical field overlap with absorptive material within the laser cavity.

[0008] To date, all demonstrated designs of VCSELs have compromised between their optical and electronic characteristics. Designs that optimize optical quantum efficiency minimize electrical conductivity, and vice versa.

[0009] In a recent effort to solve the high series resistance problem, Kwon et al. in U.S. patent No. 5,034,958 entitled "Surface Emitting Diode" describe a VCSEL comprising a laser cavity disposed between upper and lower mirrors, with an active region sandwiched between the upper and lower spacers. The lower mirror includes a distributed Bragg reflector (DBR), whereas the upper mirror includes a dielectric DBR. An electrical contact layer comprising two pairs of p-type doped GaAs/AlAs semiconductor layers which form a semiconductor DBR is disposed between the upper dielectric mirror and the upper spacer for injecting current into an upper portion of the active region.

[0010] The VCSEL of Kwon et al. further comprises a contact region having a high conductivity increasing ions injected into the active region from the cavity between the active layer and the dielectric DBR. In this structure, electrical current is injected through one or two pairs of GaAs/AlAs semiconductor layers to reach the upper spacer and then injected into the active region instead of the typical 20-30 pairs in a conventional DBR. Consequently, the series resistance of the DBR structure is reduced.

[0011] Despite this improvement, the VCSEL, in comparison to edge emitting lasers, still has a high series resistance which is still high, limiting its performance. One reason for the high series resistance is the low doping concentration in these semiconductor layers. From the typical $10^{18}/\text{cm}^3$ to $10^{19}/\text{cm}^3$ doping concentration, it would further reduce the series resistance if the doping concentrations prohibitively increased. However, this would reduce quantum efficiency and thus the overall performance.

[0012] Another problem with the VCSEL is that they tend to operate in higher order transverse modes, whereas edge emitting lasers operate in the fundamental TEM₀₀ mode.

[0013] Therefore, there is a need for a VCSEL which has a high optical power output, a low series resistance, and single transverse mode operation to

reduce the series resistance of VCSELs without substantially compromising their optical quantum efficiency so as to improve their power efficiency.

[0014] It is another object of this invention to suppress higher-order transverse mode lasing within VCSELs.

SUMMARY OF THE INVENTION

[0015] These and other objects are achieved in accordance with the invention in vertical-cavity surface-emitting lasers (VCSELs) that utilize intra-cavity structures to reduce the series resistance and achieve single transverse mode TEM₀₀ operation. The intra-cavity structures include a stratified electrode, a stratified electrode with a current aperture, and/or an optical aperture.

[0016] In one preferred embodiment of the invention, a VCSEL comprises a laser cavity disposed between upper and lower distributed Bragg reflector (DBR) mirrors. The laser cavity comprises upper and lower spacers surrounding an active region that generates optical radiation. A stratified electrode is disposed between the upper mirror and the upper spacer for conducting electrical current into the active region to cause lasing. Alternatively, the stratified electrode can also be disposed within the upper mirror, preferably below most of the upper mirror.

[0017] The stratified electrode comprises a plurality of alternating high and low doped semiconductor layers of the same conductivity type, vertically stacked with respect to the active region. During lasing, a standing wave with periodic intensity maxima and minima is established in the laser cavity. The high doped layers of the stratified electrode are positioned near the standing wave minima, separated by the low doped layers positioned near standing wave maxima. This arrangement produces a high transverse conductance in the stratified electrode without substantially increasing optical absorption and, as a result, greatly reduces the series resistance without compromising the optical efficiency.

[0018] In another embodiment, in combination with the stratified electrode, an electrical current aperture having a diameter smaller than the laser cavity optical aperture is used to suppress higher-order transverse mode lasing. This current aperture substantially reduces current crowding at the peripheral portion of the active region and increases electrical current density at the center of the active region. As a result, higher-order transverse mode lasing is eliminated.

[0019] The electrical current aperture is a disk shaped region homocentrally located between the upper mirror and the active region. It is defined by an ion implantation of conductivity reducing ions into the annular surrounding area. The electrical current aperture is vertically aligned to the center of the upper mirror, and has a diameter equal to or smaller than that of the upper mirror. The implanted area that defines the current aperture has a conductivity reducing ion concentration such that, in the implanted area, the low doped p layers have

a high resistivity while the other layers remain conductive. Therefore, when current is applied to the stratified electrode, the current is substantially parallel to the active region, and is then vertically injected into the active region. In this manner, the transverse mode TEM₀₀ operation is achieved.

[0020] In another embodiment of the invention, a VCSEL comprises a laser cavity disposed between upper and lower DBR mirrors. The laser cavity comprises upper and lower spacers surrounding an active region. The upper and lower spacers are DBRs which comprise sequential layers of high and low index of refraction layers. The upper spacer is further defined as having a gain region formed within the active region by an ion implantation of conductivity reducing ions in a plane parallel to the active region and disposed within the upper DBR mirror. Preferably, the gain region is placed within only a few layers of the upper DBR mirror above a top p layer. The metal layer has an opening which is aligned to the gain region and has a diameter smaller than that of the gain region. This opening acts as an optical aperture that blocks higher order transverse modes to eliminate higher order transverse mode operation, resulting in single transverse mode operation. In addition, the metal layer has a distributed ohmic-metal contact, thereby reducing the series resistance by reducing the number of resistive layers through which current must pass to reach the active region.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] These and other objects, features, and advantages of the present invention will be more apparent from the detailed description of the invention with the appended drawing.

Fig. 1 is a cross-sectional view of a VCSEL with an intra-cavity first stratified electrode in accordance with the invention;
Fig. 2 is a cross-sectional view of a VCSEL with intra-cavity first and second stratified electrodes;
Fig. 3 is a cross-sectional view of a VCSEL with an intra-cavity stratified electrode and a current aperture;
Fig. 4 is a cross-sectional view of a VCSEL with an upper mirror and an intra-cavity first stratified electrode;
Fig. 5(a) is a cross-sectional view of a laser cavity showing the standing wave intensity with respect to the layers in the laser cavity;
Fig. 5(b) is a cross-sectional view of the layers in the laser cavity showing their vertical positions;
Fig. 5(c) is a cross-sectional view of the layers in the laser cavity showing their vertical positions;
Fig. 5(d) is a cross-sectional view of the layers in the laser cavity showing their vertical positions.

Fig. 11 is a cross-section of a VCSEL with an intracavity optical aperture and an optical gain region surrounded by a regrowth material.

[0026] Electrical current passes from electrical contact 80 to first stratified electrode 50, then to spacer 50, active region 40, spacer 30, mirror 20, substrate 10 and finally to bottom electrical contact 90. Since electrical current is conducted through the stratified electrode into the active region, upper mirror 20 does not need to be conductive. Advantageously, this allows the VCSEL to utilize an upper dielectric DBR mirror. Dielectric layers

[0030] Furthermore, the

a VCSEL with a strat-
ed electrical current

[001] is shown in Fig. 1, lower mirror 20 comprises alternating layers 21, 22 of n -doped AlAs and AlGaAs, respectively. Each layer is a $\lambda/4$ thick, where λ is the wavelength of the emitted radiation. For a detailed description of the epitaxial growth of semiconductor [001] structures, see, for example, J. Jewell et al., "Vertical-Cavity Surface-Emitting Lasers: Design, Growth Fabrication, and Characterization," *IEEE Journal of Quantum*

1000 Å. Fig. 5 shows the energy band structure of the layers in stratified and homogeneously doped GaAs. The high-doped Al_{0.3}Ga_{0.7}As layer is assumed to be the energy barrier for the electrons. This results in the stratified structure having a concentrated hole population in the Al_{0.3}Ga_{0.7}As layer, spilling over to the GaAs and Al_{0.3}Ga_{0.7}As layers. In GaAs, the α value is greater than in the doped layers, resulting in stratified electrons. It is therefore evident that the efficiency of the laser is substantially improved.

band diagram of the structure is shown in Fig. 1. The energy levels of the H₂ molecules are taken from each of the two molecules herein due to the Al_{0.15}In_{0.85}GaP interlayer. The interlayer has a high conductivity and is used as a contact layer from the substrate. Alternatively, the interlayer can be InGaAs and Al_{0.15}In_{0.85}GaP where y is a parameter high and low conductivity. The intra-cavity energy level is as low as possible and the energy level without the interlayer is as low as possible. The quantum effi-

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shown in Fig. 9, a 1- μ m-f-dBR mirror (200 Å), an upper 1.2- μ m-f-dBR (200 Å). A metal layer 15 is formed within the upper portion 275 into an upper portion consisting of gold and a thin contact layer 250. Advantages of this design are that only a few pairs of layers in low series are needed to achieve a 10-dB loss, and the loss is independent of the wave-length λ .

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Typically
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the gain in strength with an increase in the amount of glass by 10% is 10% for a mass of 100 g of material. Therefore, the materials are non-toxic and are regionally available. The latent heat of fusion is 100 J/g, and the specific heat is 1.5 J/g°C.

nation.

[0051] As shown in Fig. 11, another means to define the optical gain region is, after vertically etching down the surrounding region below the active region, to vertically regrow around the optical gain region with a material having a high resistivity and lower index of refraction than that of the active region. For example, undoped AlGaAs region 227 may be regrown to surround sidewall 225.

[0052] The optical effects of metal layer 260 on the laser cavity can be tailored by varying its thickness and location. For making metal layer 260 about 100Å thick or less, its optical absorption can be made small. Furthermore, by providing a thin metal layer such as this in an intensity minimum of standing waves, its optical absorption can be negligibly small. The optical absorption effects of metal layer 260 can thus be continuously tuned by varying its thickness, its location, and the diameter of its aperture.

[0053] The process for constructing the above structure begins with growing lower mirror 210 on substrate 200, followed by a sequential growth of lower spacer 220, active region 230, upper spacer 240, and first upper mirror portion 250. Then the optical gain region with a desired diameter is defined by etching the surrounding region vertically down below the active region that results in a mesa structure revealing sidewall 225. Following the etching, AlGaAs is regrown to the same height as the mesa structure so as to form a planar surface. Metal layer 260 is then deposited and optical aperture 265 is etched, followed by the deposition of the dielectric layers that form second upper mirror portion 270. Dielectric mirror 270 is then defined and electrical contacts 280 and 290 made to the metal layer and the substrate, respectively.

[0054] The above regrowth structure has several advantages. First, the implanted structure provides a larger index of refraction than between the active region and the substrate. Second, the implanted structure does the implanted structure. Hence, the light is better confined in the regrown region. Third, the implanted structure, thereby, improves the optical quantum efficiency of the resulting smaller diameter lasers to be made.

[0055] Second, the regrowth planarizes the VCSEL structure and facilitates electrical contact. In free standing devices, the small size of the devices, due to their small sizes, it is difficult to make electrical contacts to the top portion of the device. With the regrown structures having a planar surface, electrical contact to the top portion of the device can be made. Furthermore, the regrowth process will damage produce on the surface can terminate dangling bonds and reduce the recombination.

[0056] Various variations in the invention will be apparent to those skilled in the art from the foregoing description. For example, a single stratified electrode

can be placed between the spacer in the VCSEL structure. The spacer may be replaced with a material having a lower index of refraction than the active region material. Additionally, upper mirror portion 250 can be divided into upper and lower portions, above and below stratified electrode, analogously to the division of upper mirror 110 in

Fig. 1, 2, 3 and 8 can be divided into upper and lower portions, above and below stratified electrode, analogously to the division of upper mirror 110 in Figs. 9, 10 and 11.

Claims

1. A vertical-cavity surface emitting laser comprising:

a substrate;
a first mirror on said substrate;
a first spacer on said first mirror;
an active region on said first spacer for emitting light;
a second mirror on said active layer;
a second spacer on said second mirror;
wherein said first and second mirrors define therebetween a laser cavity;
an optical gain region formed within said active region, said optical gain region having a diameter less than that of said active layer;
a metal layer on said optical gain region;
an optical aperture in said metal layer;
a dielectric mirror on said metal layer;
electrical contacts on said dielectric mirror;
wherein said optical gain region has a diameter of said optical gain region.

2. The vertical-cavity surface emitting laser of claim 1 wherein said metal layer has a thickness less than 400Å.

3. The vertical-cavity surface emitting laser of claim 1 or 2 wherein said optical gain region is formed approximately in the center of said active layer.

4. The vertical-cavity surface emitting laser of any of claims 1-3 wherein said dielectric mirror comprises alternating layers of high and low refractive index material, each layer having a thickness of $\lambda/4n$ where n is the index of refraction of said material and λ is the wavelength of light emitted from said laser.

5. The vertical-cavity surface emitting laser of claim 6 wherein said metal layer has a thickness less than 400Å and said dielectric mirror has a thickness less than 400Å.

6. The vertical-cavity surface-emitting laser of claim 6 wherein said lower portion is disposed below said metal layer and said lower portion comprises semiconductor layers.

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7. The vertical-cavity surface-emitting laser of claim 6 wherein said metal layer is in ohmic contact with the semiconductor layers of said lower portion for conducting electrical current to said active region.

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8. The vertical-cavity surface-emitting laser of any of claims 1 to 6 wherein said optical gain region is surrounded by an annular region implanted with conductivity modulations.

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9. The vertical-cavity surface-emitting laser of any of claims 1 to 8 wherein said optical gain region has a sidewall formed by removing materials from the annular surrounding region.

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10. The vertical-cavity surface-emitting laser of any of claims 1 to 9 wherein the annular surrounding region includes regrowth semiconductor material having a larger refractivity and a smaller index of refraction than that of said active region.

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11. The vertical-cavity surface-emitting laser of any of claims 1 to 10 wherein said metal layer is substantially gold.

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FIG. 1

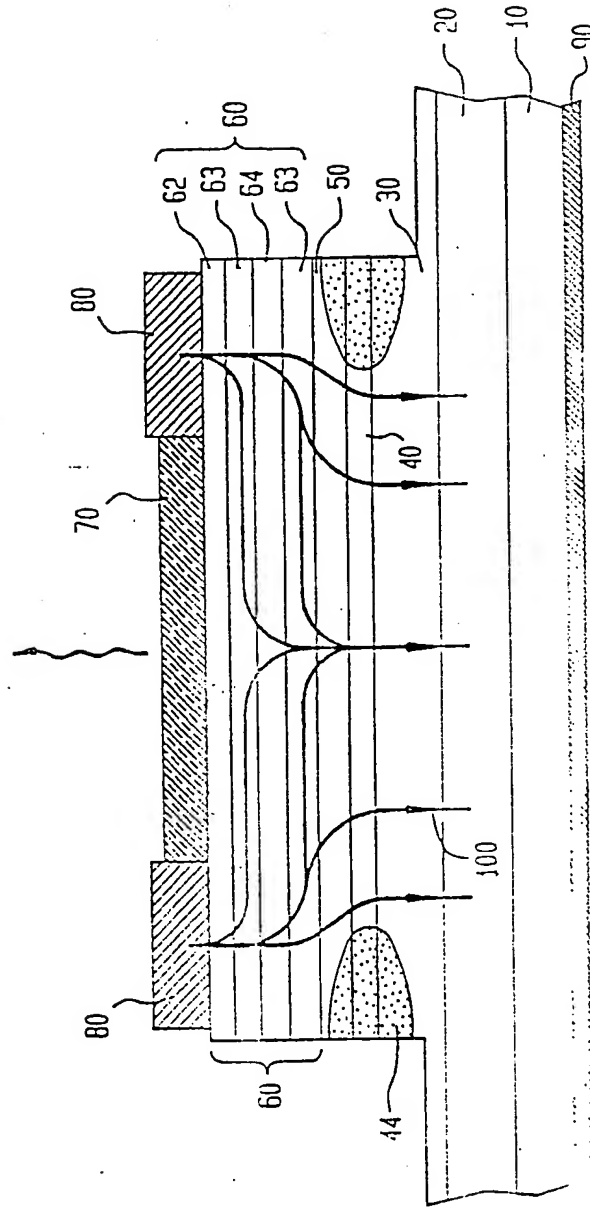


FIG. 2

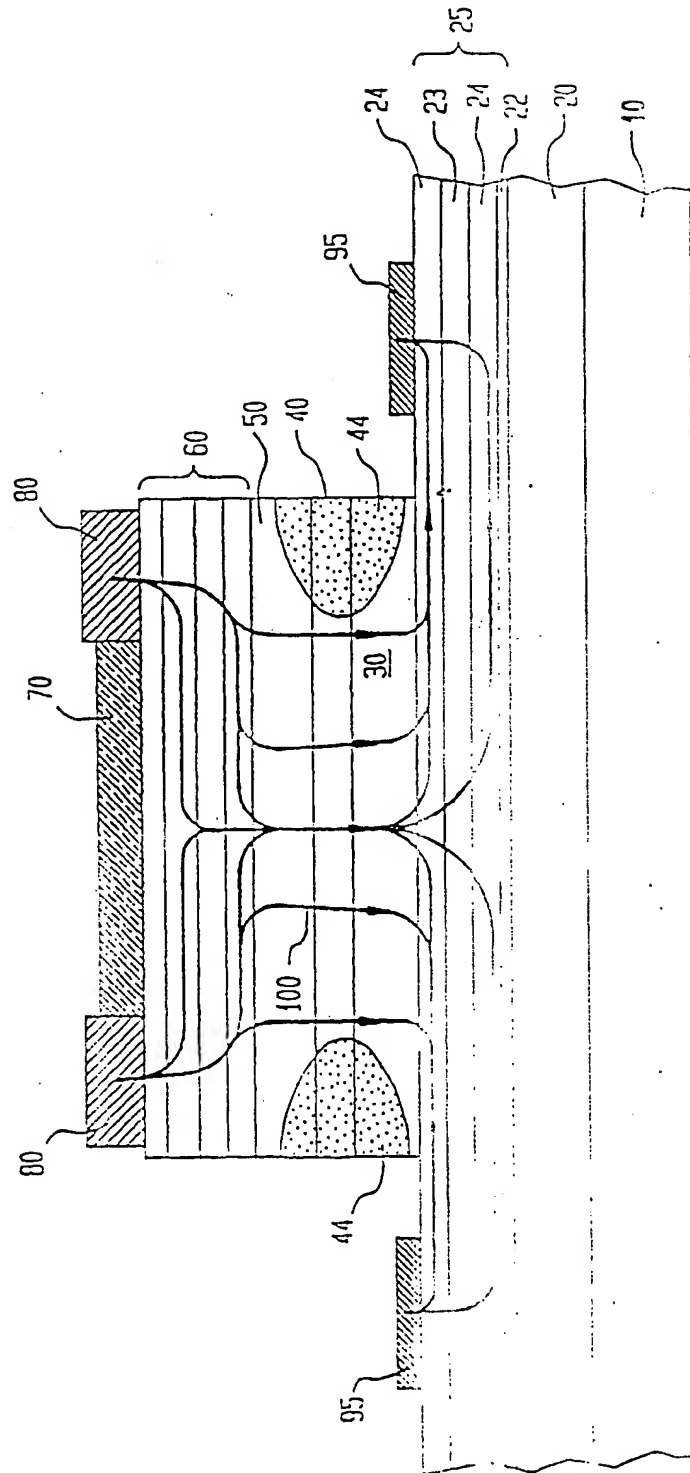


FIG. 3

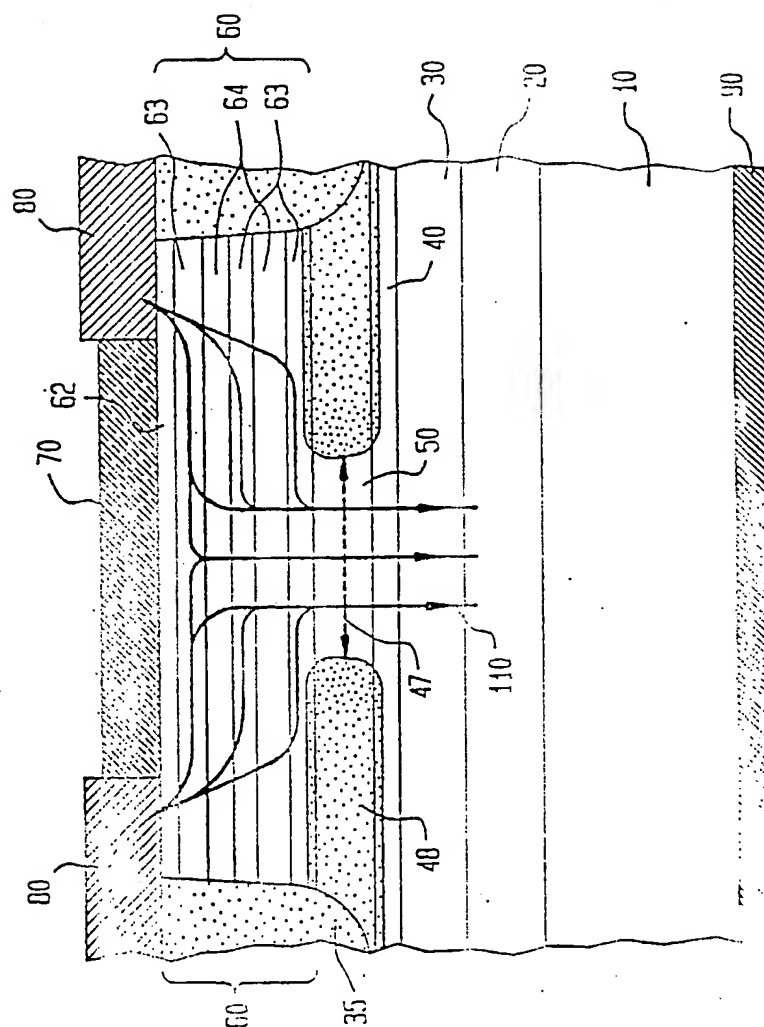


FIG. 4

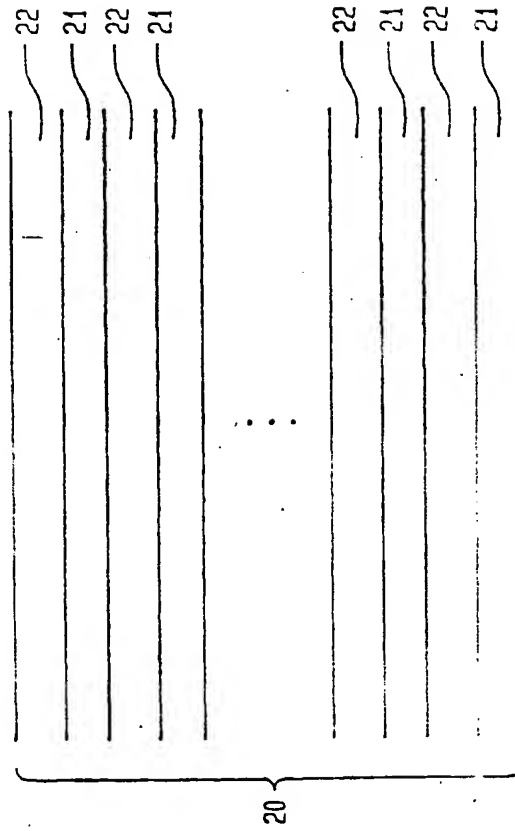


FIG. 5A

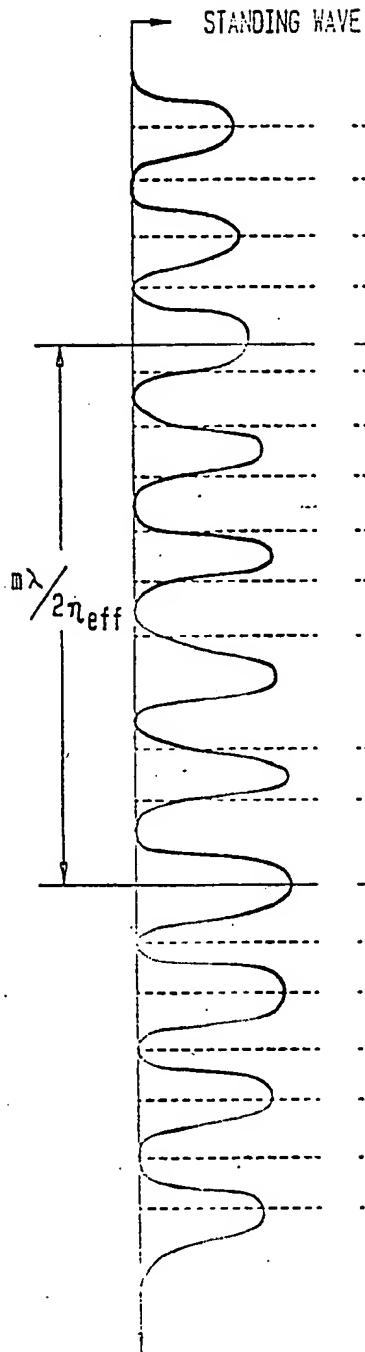


FIG. 5B

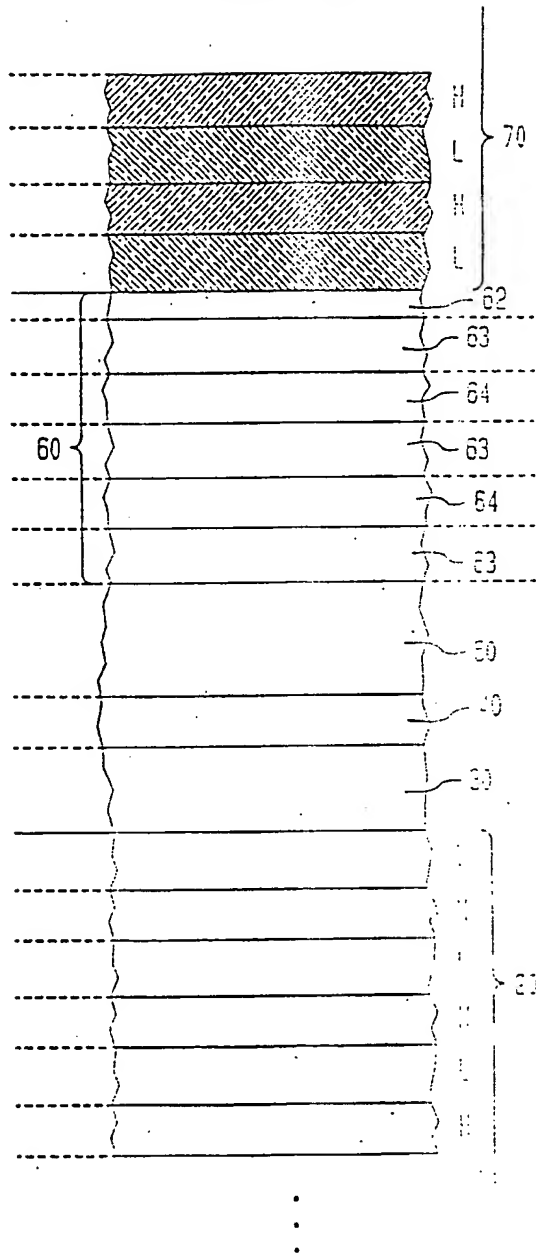
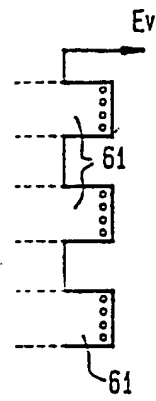


FIG. 5C



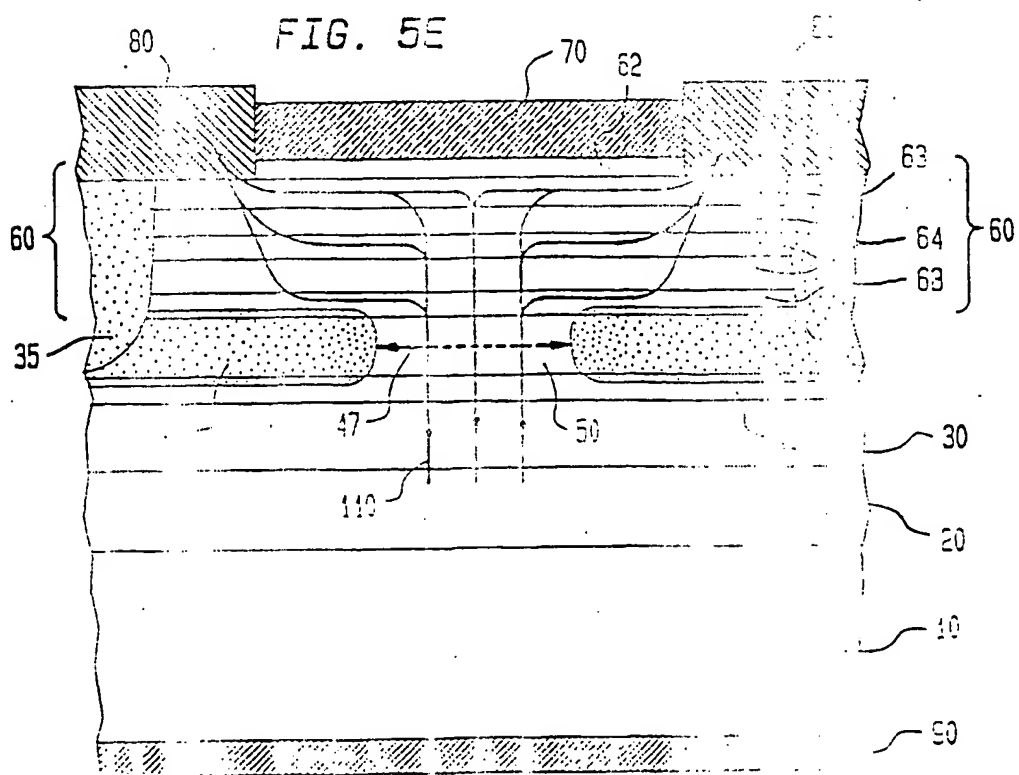
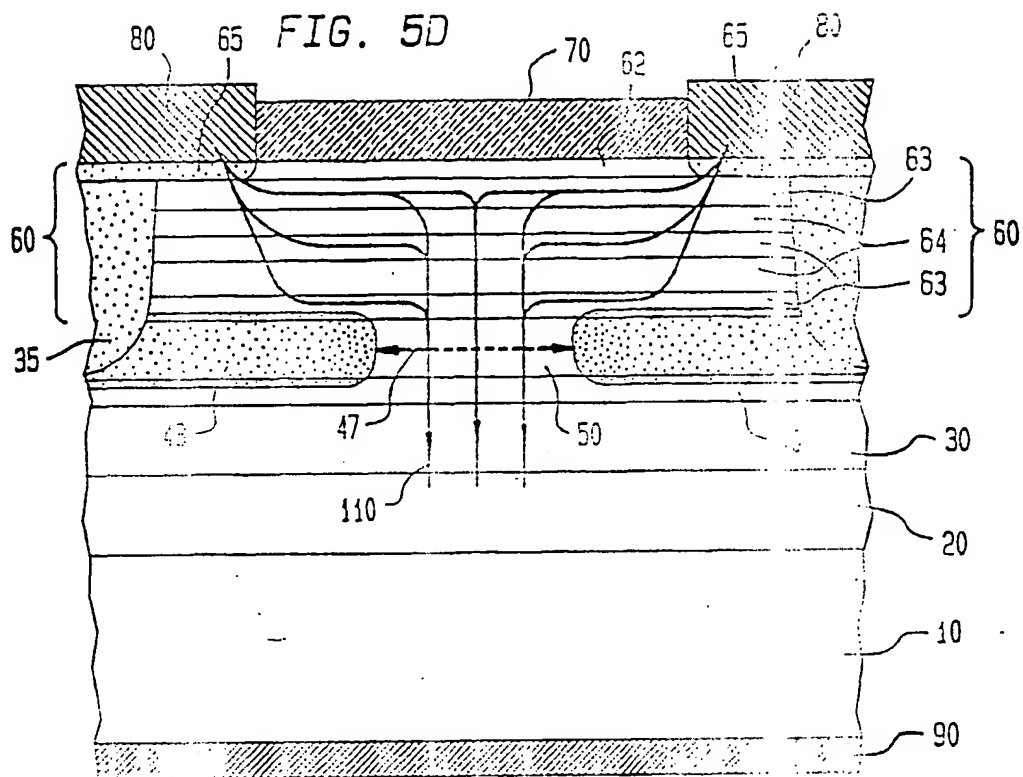


FIG. 6

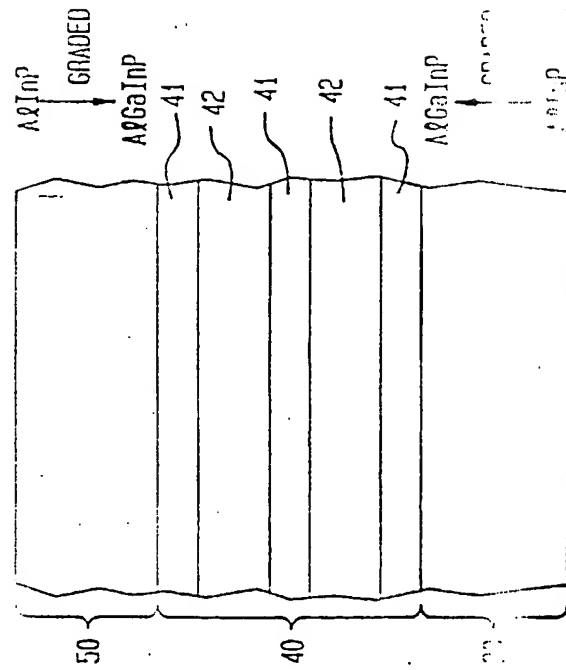


FIG. 7

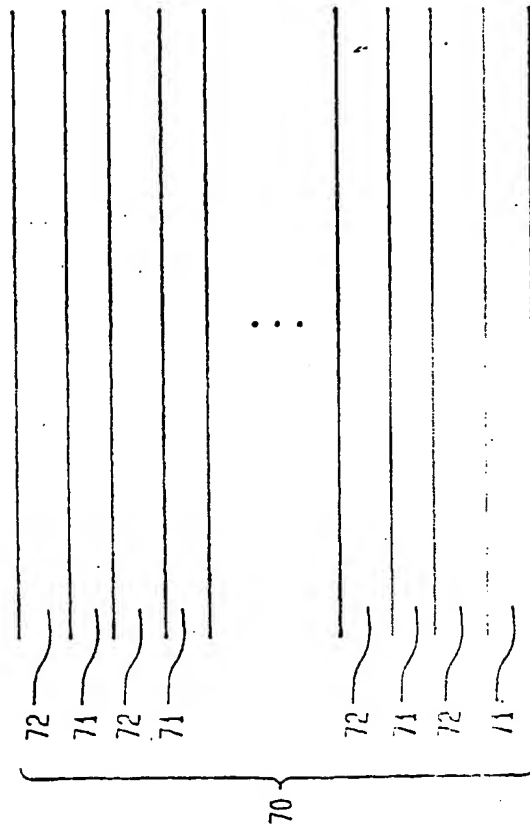


FIG. 8

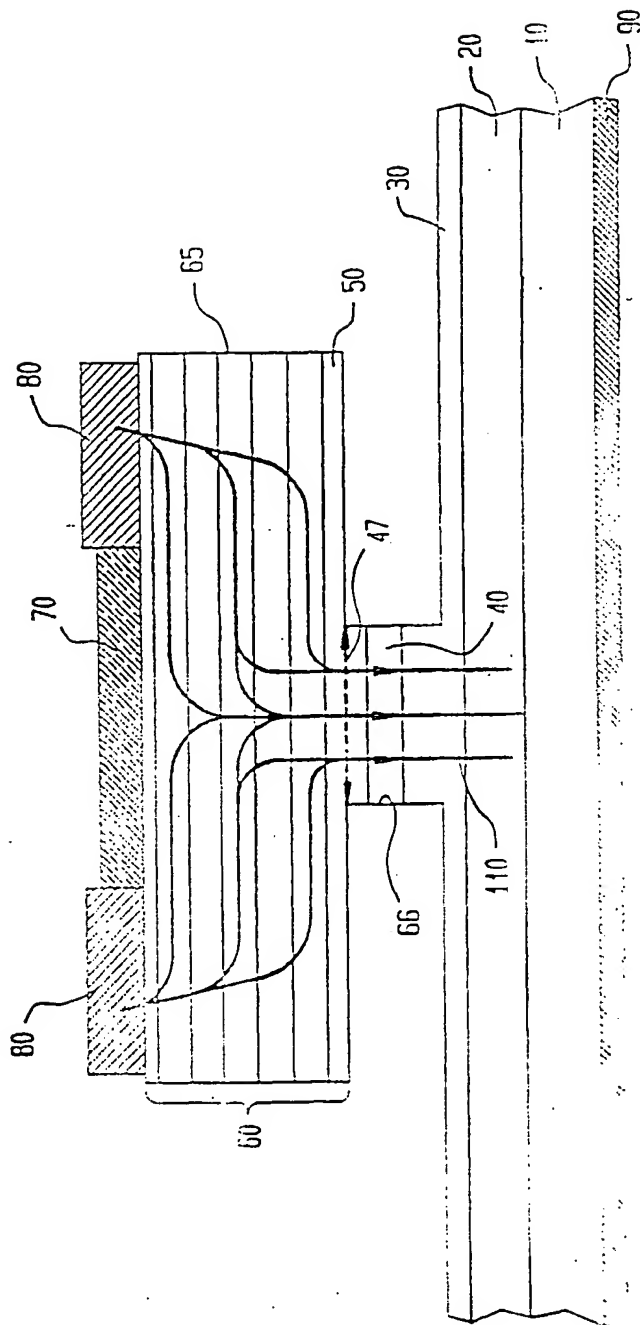


FIG. 9

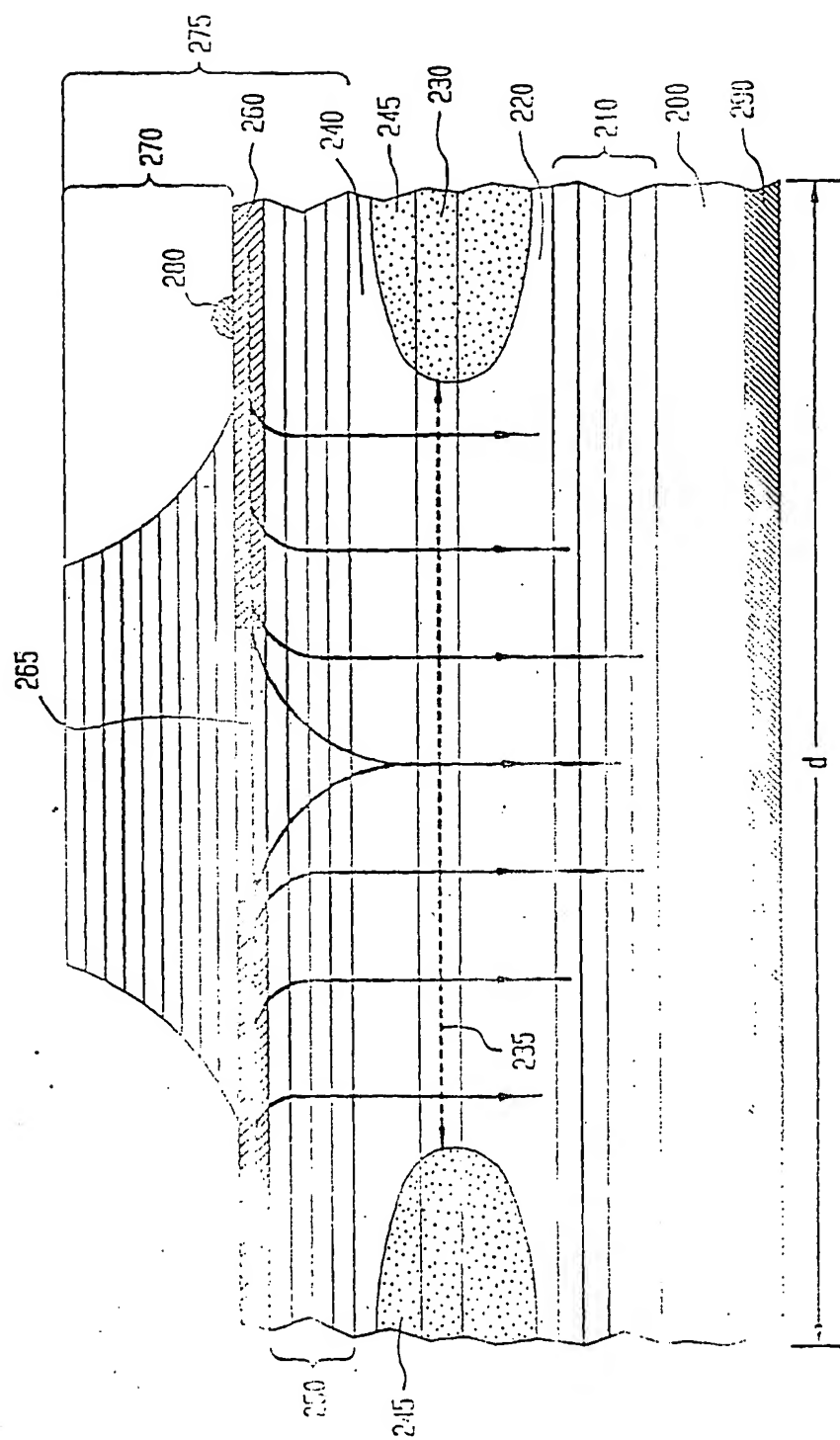


FIG. 10

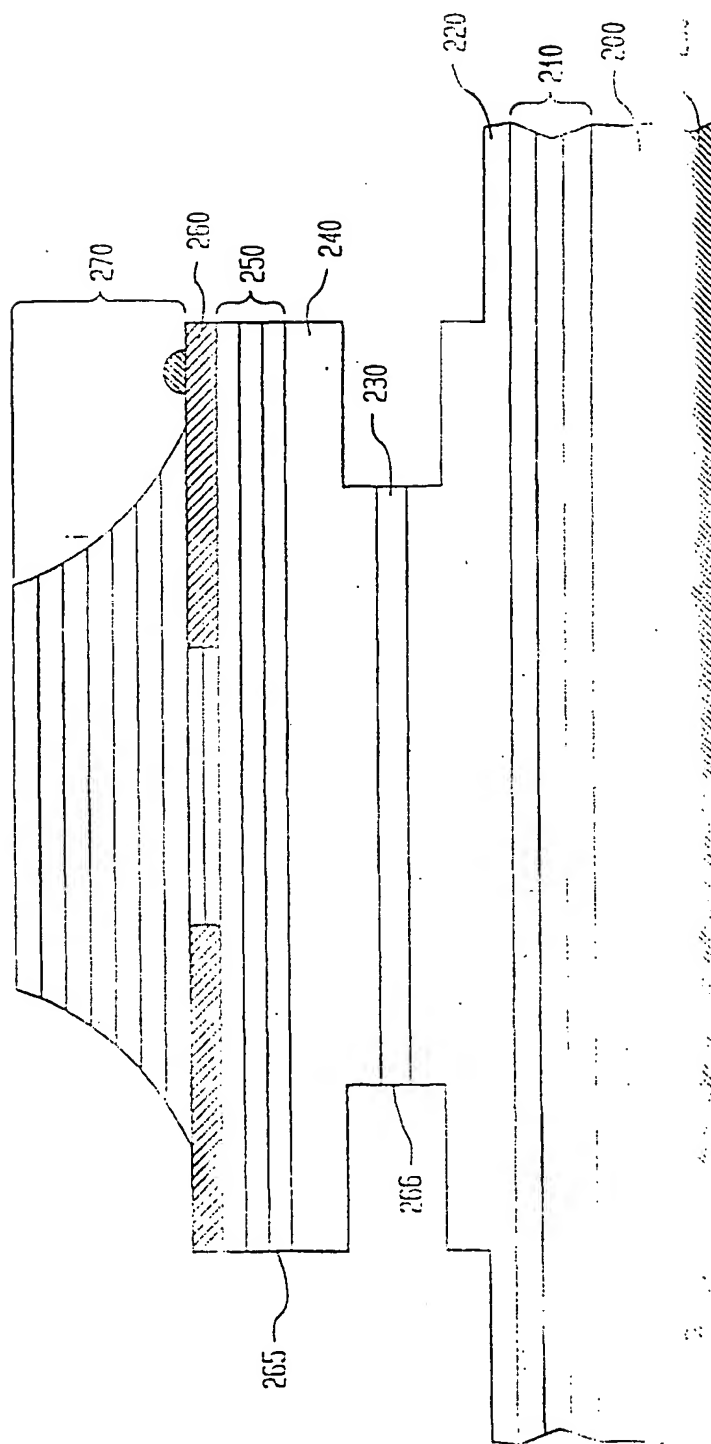
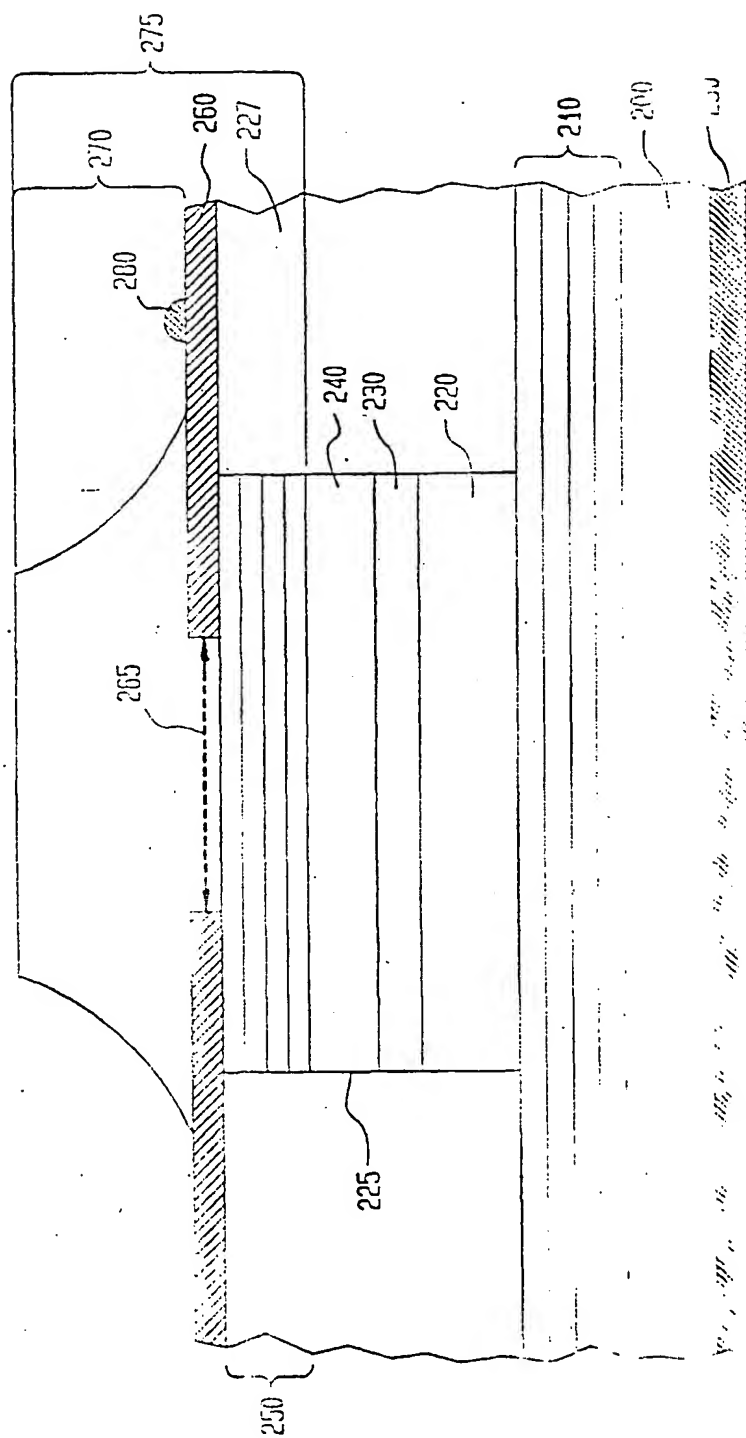


FIG. 11



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Application Number
EP 0 898 347 A1

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE DOCUMENT (Int.Cl.6)
X	EP 0 475 373 A (SEIKO EPSON CORP) 18 March 1992	1,10	H01S3/10 H01S3/05 H01S3/05
Y	* page 6, line 1 - page 7, line 20; figures 4-6 *	4-9,11	
X	K.MORI ET AL.: "Effect of Cavity Size on Lasing Characteristics of a Distributed Bragg Reflector-Surface Emitting Laser with Buried Heterostructure" APPLIED PHYSICS LETTERS, vol. 60, no. 1, 6 January 1992, pages 21-22, XP000257123 NEW YORK, US * the whole document *	1,7,10, 11	
Y	C.LEI ET AL.: "ZnSe/CaF2 Quarter-Wave Bragg Reflector for the Vertical-Cavity Surface-Emitting Laser" JOURNAL OF APPLIED PHYSICS, vol. 69, no. 11, 1 June 1991, pages 7430-7434, XP000224138 NEW YORK, US * paragraph II * * figure 1 *	4-7	TECHNICAL FIELDS SEARCHED (Int.Cl.6)
Y	K.TAI ET AL.: "90% Coupling of Top Surface Emitting GaAs/AlGaAs Quantum Well Laser Output into Small Diameter Core Silica Fibers" ELECTRONICS LETTERS, vol. 26, no. 19, 13 September 1990, pages 1528-1529, XP000106111 STANFORD, GB * the whole document *	3,11	
A		1,7	
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The search has been drawn up for all claims			
Date of completion of the search		22 October 1992	
<p> X: particularly relevant document Y: particularly relevant document with another document of the same category A: technical field of the invention O: non-written document P: intermediate document T: theory or principle underlying the invention E: earlier patent document D: document cited in the application L: document cited in other literature S: member of the state of the art document </p>			

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